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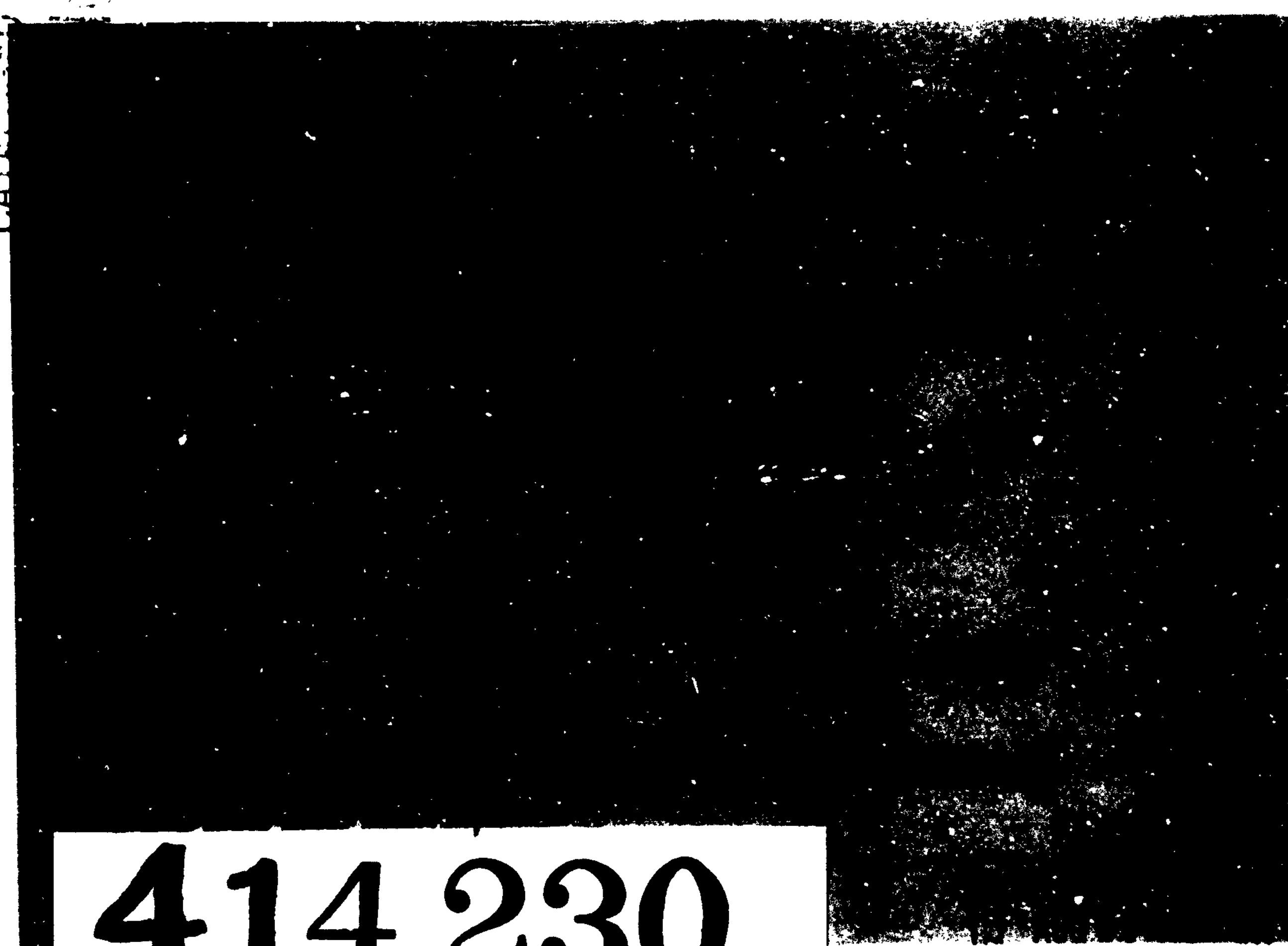

THE TRAVELERS RESEARCH CENTER INC.

The Use of Radar Summary Maps for
Weather Analysis and Forecasting

by

J. W. Wilson and E. Kessler, III

ERRATA

P. 3. Footnote. Insert "Circuits" at beginning of second sentence.

P.23. For greater clarity substitute for the sentence starting on line 4, the following: Of the subsequent echo occurrences, 82.5% were correctly forecast by translation, compared with only 69.5% by persistence.

P.29. Reference numbers in line 3 should be (5, 6, 7).

P.43. Footnote: Third line, for "range" substitute "intensities." Strike out "sets of" in fourth line.

Contract FAA/BRD-363

USE OF RADAR SUMMARY MAPS FOR WEATHER ANALYSIS AND FORECASTING

James W. Wilson
and
Edwin Kessler, III

June 19[illegible]

This report has been prepared by The Travelers Research Center, Inc., for the Aviation Research and Development Service, formerly the Bureau of Research and Development, Federal Aviation Agency, under Contract FAA/BRD-363. The content of this report reflects the views of the contractor, who is responsible for the facts and accuracy of the data presented herein. The content of this report does not necessarily reflect the official policy of the Federal Aviation Agency.

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ABSTRACT

This is a study of the application of the present U.S. radar observing and reporting system and includes suggestions for its immediate improvement.

A study of radar summary maps collected from July to December, 1961, shows that the echo areas reported are very closely associated with precipitation and that the reported echo intensities and heights of tops are valuable for assessing the occurrence of thunderstorms and other precipitation types. Use of past-hour motion arrows shown on the maps for prediction by translation gives better 3-, 6-, and 9-hr forecasts of echo areas over St. Louis, Mo., than does persistence. The symbols given to indicate the fractional echo coverage within echo areas are usefully related in summer to the probability that precipitation occurs at any point within the echo area. Such relationships can be combined with the probabilities associated with echo-area forecasts to obtain a probability for the future occurrence of echo at any particular point. Some means for extending such probability designations to route forecasts are briefly indicated.

Neither the form of the hourly reports from airways stations nor the radar-echo intensity reports are suitable for comparison of precipitation rates and echo intensities. However, some coherence in the radar intensity reports is shown by a slight tendency for the intensity over a 3-hr period to change in the direction reported at the earlier time. This tendency also indicates that the variations in echo intensity contain components with periods of 8 hr or more and that increasing precision and accuracy of the radar data will eventually warrant the consideration of these components in the preparation of operational forecasts.

A principal weakness of the present radar data observing and reporting methods is the coding scheme. The encoded echo observations are very general and the location of echoes within the areas indicated on the radar summary maps is not shown except for particularly noteworthy cases. The lack of precision in locating particular echoes is responsible for the relatively small probability (60% or less) that must usually be assigned to point precipitation occurrences. However, the present data demonstrate both that radar is a valuable aid for terminal and enroute forecasting and that forecasts of useful accuracy and greater precision should be possible when more precise radar data become available.

The results of this study are the basis of a recommendation that the present system of quasi plain-language encoding and reporting of radar echoes be abandoned in favor of a digital code suited for both manual and computer processing, wherein the echo reports are in a standard format and pertain to squares of about 25 mi on a side. Besides facilitating future evaluations of relationships between weather and radar echoes, such a code would provide data required for more precise forecasts.

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1.0 INTRODUCTION

The installation of WSR-57 radars throughout most of the eastern half of the United States has been spurred by aviation's steadily increasing requirements for weather data, by the need for improved management of hydrologic resources, and by the need of many interests for improved warnings of severe storm occurrences. However, the manual techniques presently in use for reporting, encoding, and plotting radar data do not take full advantage of present radar capabilities, or of modern methods for data processing and communicating.

This report is an attempt to document the operational applications of the present radar observing and reporting system and to present practical methods that can be used immediately for improving the usefulness of the radar network.

2.0 THE PRESENT WEATHER-RADAR INSTALLATIONS AND DATA-HANDLING SYSTEM

On 1 February 1962, the Weather Bureau's operating network consisted of twenty-nine WSR-57, three SP or SP-1M, one Decca 41, and sixty-three WSR-1, -1A, -3, or -4 radars. These and a joint-use radar station at Guthrie Air Force Station near Charleston, W.Va., are shown in Fig 2-1. Radar observations, made regularly at intervals of 1 hr at each station by Weather Bureau personnel, are encoded in a style that may be characterized as "abbreviated plain-language" and transmitted to Kansas City over one of three RAWARC* circuits.

The present observing procedure, described in detail in the Weather Radar Surveillance Manual,[11] requires that each observer make decisions that depend on his personal interpretation. The encoded information pertains to the location, movement, intensity, intensity change, and vertical development of isolated cells or especially strong echoes; in addition, the echo coverage is included for echoes in the form of bands, lines, or areas.† The message is a description of the radar-scope display, and its quality varies with the complexity of the patterns, the scale of elements in the patterns, the time available to make and encode the observations, and the judgment of the observer. During a study[10] of radar codes, Russo found that different observers code the same weather situation in considerably different ways, and Weather Bureau observers who were interviewed agree that considerable variability accompanies use of this code.

Any data transmitted to Kansas City on one of the RAWARC circuits are

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*RArep and WARning Coordination system. 7061, 7062, and 7063 serve the northeast, southeast, and central United States, respectively.

†Because of a delay in fitting the WSR-57's with accurate and reliable gain-control circuits and calibration equipment, intensity measurements with these radars have been semiquantitative at best. Comparative measurements of the intensities of echoes on the older WSR-1, -3, and -4 and SP radars have been even less satisfactory. However, it is planned to have all WSR-57's fitted with accurate gain-control circuits by the summer of 1962 and more valuable intensity measurements with these radars should then be possible.

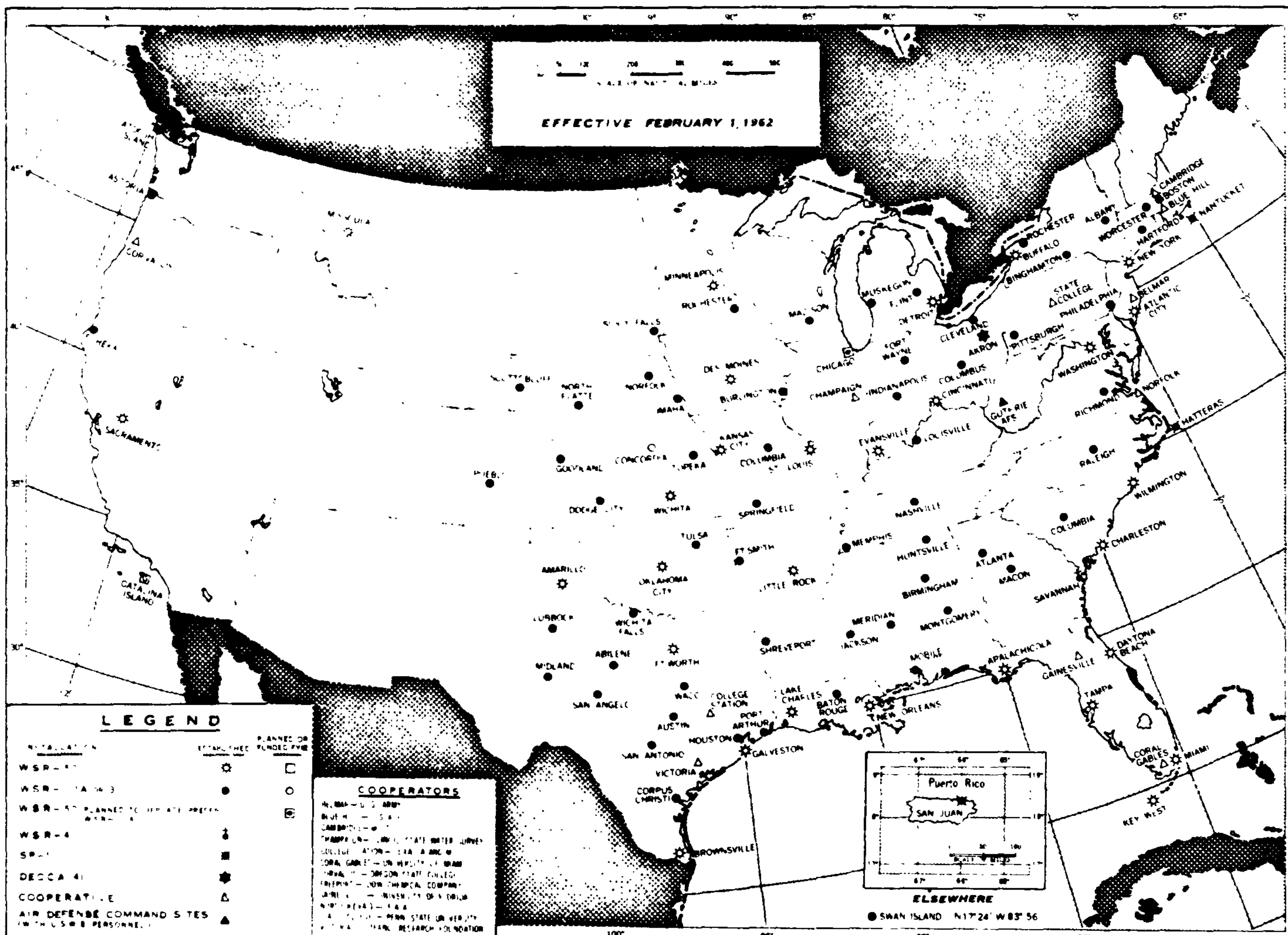


Fig. 2-1. Distribution of radars for weather observation.

also available to all others receiving on that circuit Thus, some of the unedited information is used by Air Traffic Control Centers, flood forecasters, and others who need timely information, especially when the weather is stormy.

At Kansas City, the hourly data carried by the three RAWARC circuits* are combined by two or more meteorologists of the Radar Analysis and Development Unit (RADU), who prepare an abbreviated plain-language summary of the weather in each of the three sections of the country served by a RAWARC circuit. Like the data originating at the radar sites, these summaries are transmitted hourly over their corresponding circuits In addition to the hourly summaries, a map showing the radar weather observations over the entire nation is prepared each hour and one is transmitted over the national facsimile circuit at 3-hr intervals The transmitted map shows the echo distributions by means of a self-evident code. The elements reported on the map include echo coverage, movement, intensity, intensity change, type, and vertical development Some of this information is often omitted: however, the echo coverage, intensity, height, and area movements are reliably reported Figure 2-2 is a section of an actual radar map, with an explanation of the symbols used.

Since the analysis of the radar summary map is subjectively drawn, it is desirable to recognize the guides used by the analyst who prepares it. This information was obtained from Mr. H. E Foster, Chief of RADU.[3] According to Mr. Foster, the analyst's most stringent requirement is to remain abreast of the meteorological situation, and to use this knowledge in the interpretation of the reported echoes Basically, the echo locations and motions, as well as tops and intensities occurring on the summary, are directly as reported (except for

*Sometimes reference is also made to observations made at CPS-9 sites and received at Kansas City over Air Force lines Although the attenuation common to 3-cm observations during heavy precipitation limits nationwide use of CPS-9's in summer, the great sensitivity of these radars, and the absence of 3-cm attenuation in dry snow, should make the CPS-9 observations of marked value in winter

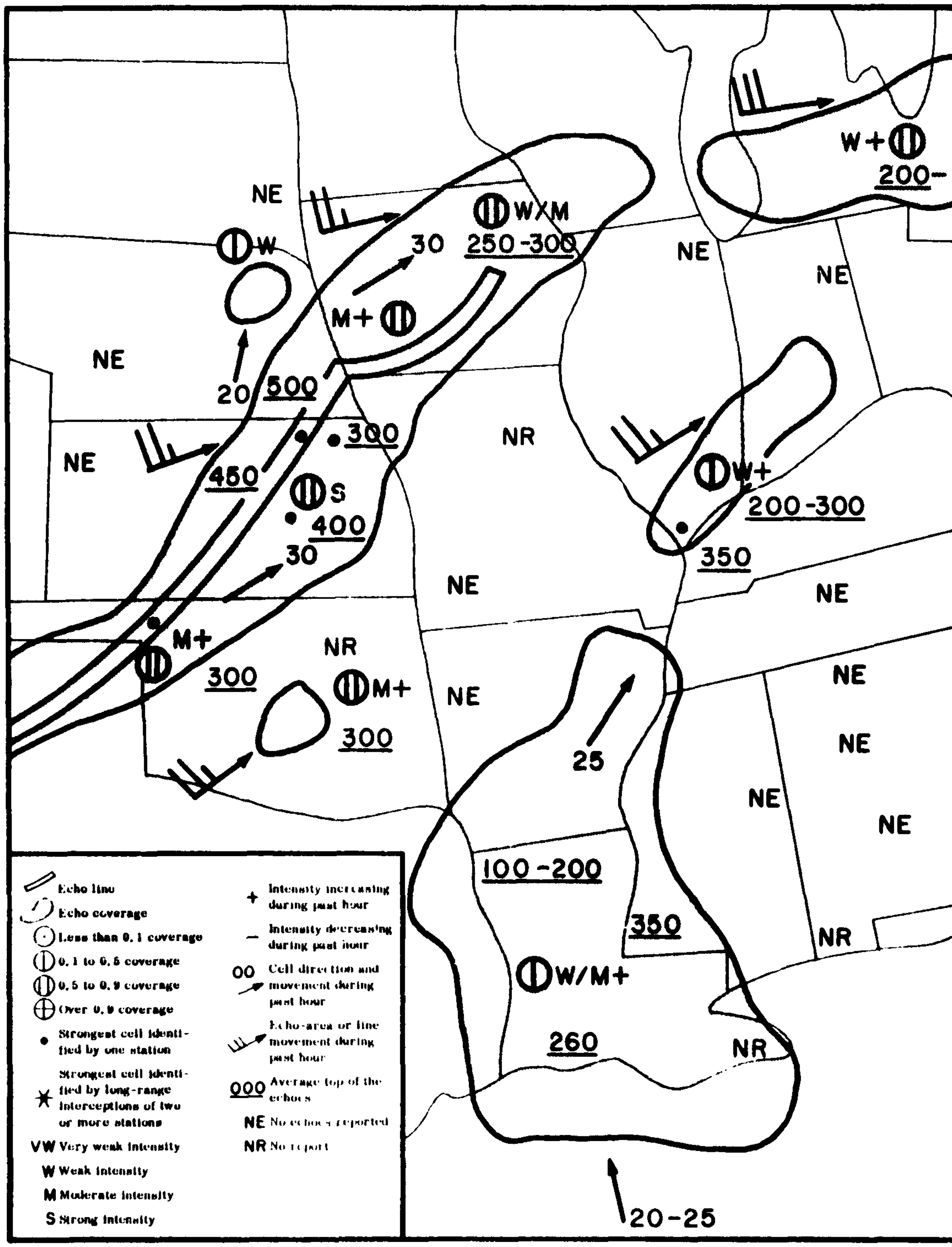


Fig. 2-2. Traced section of the radar summary map of 2100Z October 29, 1961, as received by facsimile at The Travelers Weather Service.

an "averaging" of those overlapping reports which disagree). The shapes of areas or the exact way in which the various reports are consolidated depends to a certain extent upon the synoptic situation. According to Mr. Foster, the analyst tries to consolidate the various echoes in an area to fit the known synoptic situation. Quite frequently, the lines or area movements are calculated at RADU by comparison with the previous hour's position.

In short, the Kansas City meteorologists combine overlapping reports, reduce errors, and produce a summary which, as shown below in this report, is a fair description of the distribution of precipitation.

3.0 INTERPRETATION OF THE RADAR SUMMARY

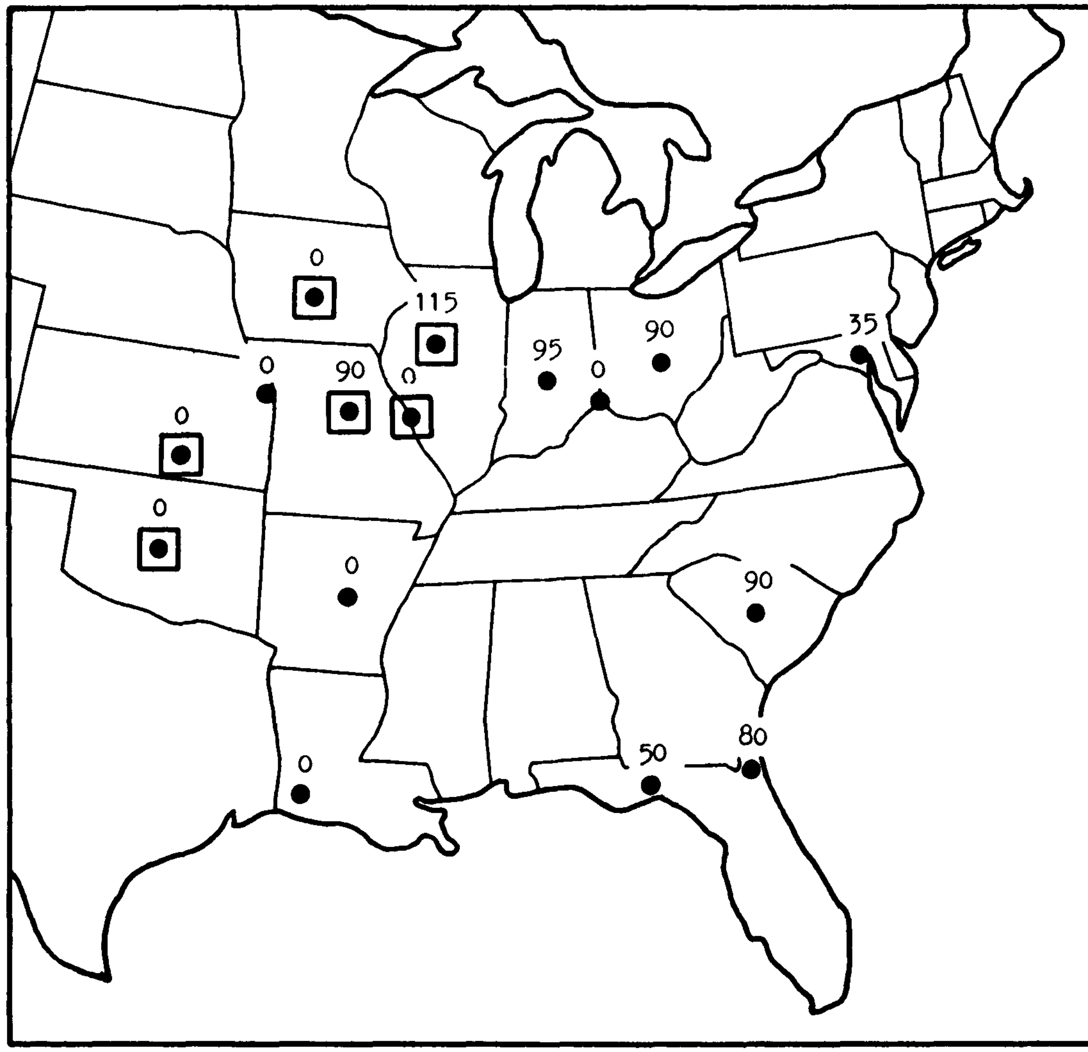
3.1 Correspondence of Echo Areas with Surface Precipitation

To assess the usefulness of the radar summary for describing the weather, several studies were made to relate the occurrence of echoes, and categories of echo intensity and echo tops, to the weather.

The first study involved the correspondence between echoes reported on the radar summary and surface precipitation. One hundred radar summaries were chosen at random from those received at The Travelers Weather Service office late in the summer and during the fall of 1961. The occurrence or absence of an echo area over 16 selected stations was noted on each of the 100 radar summaries and recorded with the surface precipitation reported by the concurrent surface map. The stations used in this test are shown in Fig. 3-1. All are within 115 mi of a WSR-57 radar.

Table 3-I shows the relationship between precipitation reports on the surface chart and echo areas. The table shows that 87% of precipitation heavier than drizzle is labeled by an echo area, and that drizzle is not usually associated with echoes reported on the radar summary charts. On the other hand, selected stations within radar echo areas reported precipitation only 54% of the time. This percentage is not higher because the boundaries indicated on the radar summary refer to the echo areas and not to the individual echoes. The density of echoes within the indicated boundaries are reported in four categories ranging from widely scattered to solid [⊖ (<1/10). ◐ (1/10 to 5/10). ● (6/10 to 9/10), and ⊕ (>9/10)]. Therefore, the indication of an area boundary surrounding a station implies only a certain probability that echo exists over the station.

The relationships shown in Table 3-I lead to the expectation that the proportion of precipitation-reporting stations within an echo area increases with the reported density of echoes within the area. To test this premise, the echo density and surface precipitation were recorded for all the available data from the end of July until December 1961 for the following six Midwestern cities shown in Fig. 3-1:



● Stations used in constructing Table 3-I

□ Stations used in constructing Tables 3-II, 3-III, 3-IV, and 3-V

90 Number appearing to north of station indicates number of miles to the nearest WSR-57

Fig. 3-1. Distribution of stations reporting surface weather conditions used for comparisons of radar and surface weather reports.

TABLE 3-1

CORRESPONDENCE OF PRECIPITATION TO ECHO AREAS*

Echo area?	Number of Cases			
	No precipitation	Drizzle	Precipitation other than drizzle	Total
Yes	73	3	82	158
No	1278	11	12	1301
Total	1351	14	94	1459†

*Based on the reports of 16 selected stations on 100 pairs of surface weather and radar echo maps.

†The total number of cases is only 1459 instead of the expected 1600. The difference is the number of unreadable surface reports.

Peoria, Des Moines, St Louis Columbia, Wichita, and Oklahoma City. The results appear in Table 3-II which does indeed show that the probability of precipitation at the surface increases with reported echo coverage. However, the probability of precipitation corresponding to the ◐ and ◑ classifications shows seasonal variation, as indicated by Table 3-III.

It is instructive to consider why the frequency of precipitation associated with reports of broken and scattered echoes is greater in autumn than in summer. This seasonal variation is probably best related to the tendency of precipitation to be more stratiform during the cold season, when its intensity is less. Therefore much of the cold-season precipitation, being very light, remains undetected by radar. The greater percentage of stations reporting precipitation in scattered (than in broken) echo areas during autumn is perhaps best explained in terms of the statistical properties of small samples.

The percentage of stations reporting precipitation when echoes are broken shows an even greater seasonal variation with the months of September and October 1961 omitted than is shown by Table 3-III. In July and August, 32% of stations inside broken areas reported precipitation, compared with 80% in November and December.* This seasonal variation seems real and should be considered in making operational interpretations.

3.2 Relationship Between Precipitation Type and Height and Intensity of Echoes

Donaldson[2] and others have reported that the intensity of convective storms increases with the height and intensity of associated radar echoes. Since the intensity and height of the echo areas are reported regularly on the radar summary, a study was made relating them to the type and intensity of

*The "broken coverage" designation is applied when observed echoes cover more than half an area. The occurrence of precipitation with only 32% of surface reports within such areas is probably due to more extensive echoes aloft, where the radar beam is, than at the ground.

TABLE 3-II

ECHO COVERAGE vs PRECIPITATION OCCURRENCE*

Echo coverage†	Number of cases	Percentage with precipitation
⊕	10	100
⦷	276	59
⦶	84	40
⊙	8	0

*Based on six Midwestern stations reporting surface weather, and all available pairs of surface weather and radar summary maps from July to December 1961.

†For definition of symbols, see p. 9.

TABLE 3-III

BREAKDOWN BY SEASONS OF DATA GIVEN IN TABLE 3-II

Echo coverage	Jul-Sep 1961		Oct-Dec 1961	
	Number of cases	Percentage with precipitation	Number of cases	Percentage with precipitation
⊕	8*	100	2	100
⦷	150	50	128	69
⦶	64	16	20	70
⊙	7	0	3	0

*Seven of the overcast cases were associated with one large persistent echo area associated with the remnants of Hurricane Carla after it passed inland.

precipitation occurring at the surface. For the same six stations and time periods discussed above, the relationship between reported hydrometeor types and the radar echoes is given by Table 3-IV. This table is suitable for use by the practicing forecaster, who must proceed from a knowledge of the echoes to the probability that a given type of weather will occur. For example, the probability that an echo of greater than moderate intensity over a particular point is associated with a thunderstorm at that point is given by 0.77 times the entry from Table 3-III corresponding to the given coverage symbol and season.

Since light or moderate rates are common to all precipitation types, it is not surprising that Table 3-IV fails to show a notable discrimination of precipitation type by echoes of weak and moderate intensity. Thus, the presence of weak echoes is not a sufficient criterion for estimating snow, since light rain and drizzle also give weak echoes. Common meteorological sense dictates the use of the bright-band height* at the radar station and the known or deduced distribution of surface temperature as the most important aids in the proper association of echoes and snow.

Table 3-V shows the distribution of weather type in six categories of echo height. Table 3-V indicates better discrimination of weather type than is shown in Table 3-IV: this may be due in part to more accurate determination of heights than of intensities, but associated physical mechanisms cannot be ruled out.

Tables 3-IV and 3-V are combined in Fig. 3-2, where more explicit indication of echo and precipitation intensities is given than in the tables. It is evident that the echo heights and intensities, combined with surface temperatures and bright-band data should be useful for determining precipitation type.

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*The bright band, discussed extensively by Wexler,[12] for example, is a layer of enhanced radar signal, which marks the elevation at which descending snow melts to form rain.

TABLE 3-IV

DISTRIBUTION OF PRECIPITATION TYPES WITH ECHO INTENSITY*

Echo intensity	Percentage of precipitation type					
	Snow (39 cases)	Drizzle, freezing drizzle (8 cases)	Continuous rain, freezing rain, and sleet (81 cases)	Rain shower (31 cases)	Thunder-storm (41 cases)	All types (200 cases)
Greater than moderate (13 cases)	0	0	0	23	77	100
Moderate (26 cases)	0	4	27	23	46	100
Weak to moderate (32 cases)	0	10	34	31	25	100
Weak (120 cases)	27	3	52	10	8	100
Very weak (9 cases)	78	0	11	0	11	100

*Based on six Midwestern stations reporting surface weather and all available pairs of surface weather and radar summary maps from July to December 1961.

TABLE 3-V

DISTRIBUTION OF PRECIPITATION TYPES WITH HEIGHT OF ECHO TOP*

Height h of echo top, 10^2 ft	Percentage of precipitation type					
	Snow (39 cases)	Drizzle, freezing drizzle (7 cases)	Continuous rain, freezing rain, and sleet (72 cases)	Rain shower (29 cases)	Thunder-storm (42 cases)	All types (189 cases)
$400 < h$ (13cases)	0	0	0	15	85	100
$300 < h \leq 400$ (24 cases)	0	5	8	29	58	100
$250 < h \leq 300$ (38 cases)	0	0	37	26	37	100
$200 < h \leq 250$ (44 cases)	0	9	75	11	5	100
$150 < h \leq 200$ (49 cases)	41	4	43	10	2	100
$h \leq 150$ (21 cases)	90	0	10	0	0	100

*Based on six Midwestern stations reporting surface weather and all available pairs of surface weather and radar summary maps from July to December 1961.

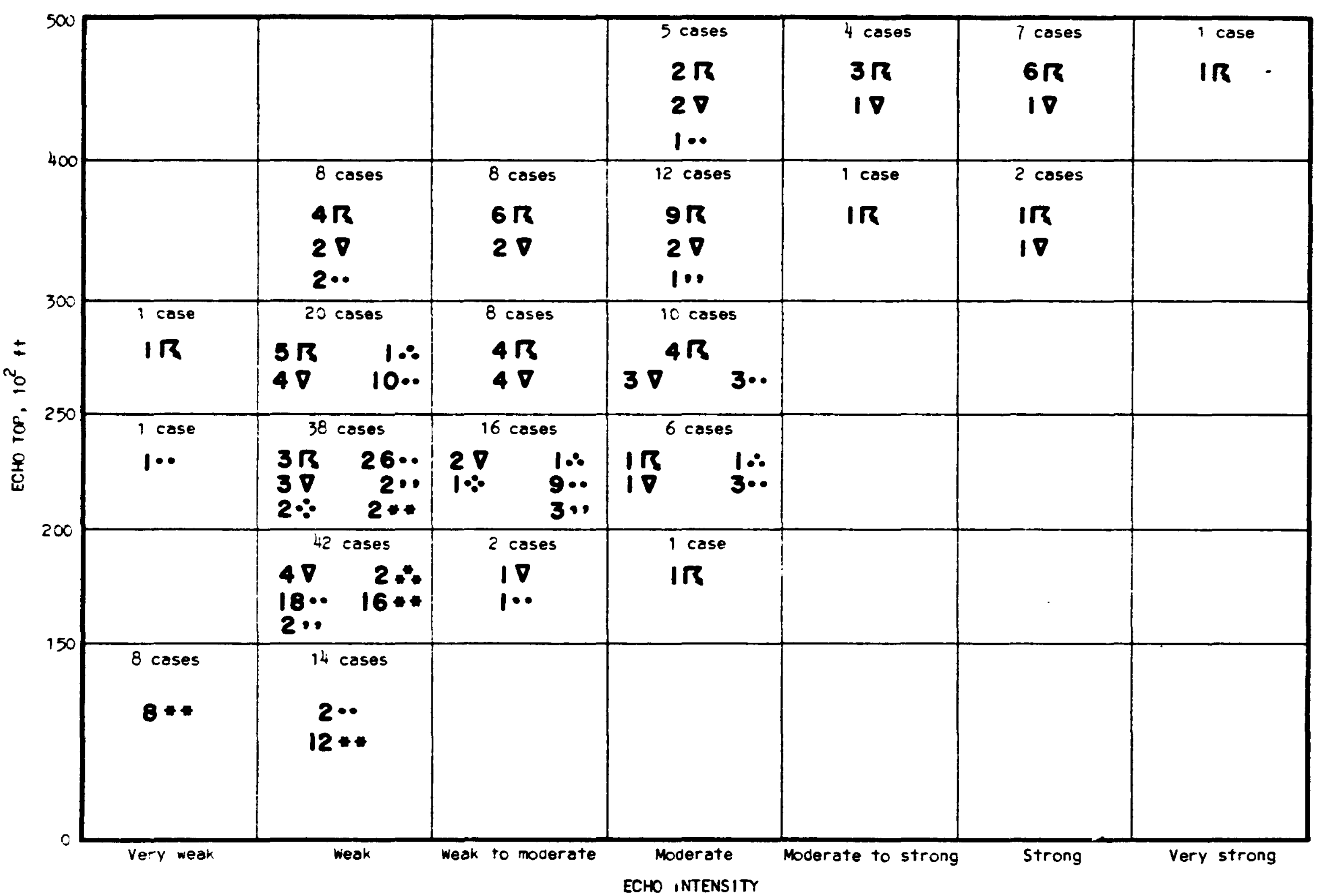

Fig. 3-2. Weather type as a function of echo intensity and echo top.

Although echo intensities seem to be sufficiently well reported to aid significantly in the identification of precipitation type, the rate of precipitation of a given type is not well related to the intensity reports. The association of 25% of the heavy-rain and thunderstorm cases with weak and very weak echoes may be indicative of inaccurate measurement of echo signal strengths. Proper assessment of this aspect of radar utilization would require the study of recording-raingauge records and point-echo intensity measurements.

4.0 FORECASTING FROM THE RADAR SUMMARY MAPS

4.1 Persistence of Echo Areas

The lifetime of a meteorological feature increases with its scale. Noel and Fleisher[8] found that linear prediction of details of a general radar echo pattern digitized in 5-mi squares shows no skill beyond 10 min. Boucher and Wexler,[1] however, have discussed the predictability of elements on the scale of a whole radar display, over periods of several hours, and show that translation gives useful several-hour forecasts of the location of a squall line or large area. However, the internal configuration of such lines or areas, being of a small scale, cannot be predicted in detail, but only in terms of suitably conservative statistical properties.

The radar summary maps provide a basis for studying some of the statistical properties of radar echo areas. Our first study concerns the relationship between persistence and size of echo areas. A random sample of 120 radar summary maps was chosen for the study. The size of each echo area on each map was measured and the map following the first by 3 hr was examined for evidence of persistence. Table 4-I shows, in six area categories, the percentage of the echo area population that was identifiable on both maps. The reader may refer to Fig. 2-2 and note that the smaller echo areas shown in Nebraska and Oklahoma have areas of about 3,000 mi^2.*

It appears that echoes whose areas are less than 1000 mi^2 seldom persist for 3 hr, whereas those whose areas are greater than about 7500 mi^2 almost always do. Since the majority of echo areas plotted on the radar summary are large, Table 4-I indicates that the maps do give meaningful information concerning the echo distribution 3 hr subsequent. The smallest echoes (little larger than the station circles on the usual surface maps) should be considered solely from the viewpoint of their historical interest.

*The unit mile throughout this report is the nautical mile.

TABLE 4-1

PERSISTENCE OF ECHO AREAS*

Area A of echo on the first chart, mi^2	Number of cases on first chart	Percentage of cases identifiable on chart 3 hr later
$10{,}000 < A$	100	100
$5{,}000 < A \leq 10{,}000$	59	85
$3{,}000 < A \leq 5{,}000$	59	76
$2{,}000 < A \leq 3{,}000$	55	67
$1{,}000 < A \leq 2{,}000$	60	57
$A \leq 1{,}000$	34	24

*All but first row based on analysis of 240 charts, Aug-Dec 1961.

4.2 Predictability of Echo Area Locations

Since the larger-scale features persist for at least 3 hr, it is of interest to examine the predictability of their locations. Of course, this problem can be viewed as one form of the classical question of precipitation prediction. Its ultimate solution must depend on the appropriate definition of initial conditions by the use of radar, radiosondes, surface observations, and other means. This report is concerned only with the extrapolative value of the information given on the radar summary maps.

The first data considered are the indicated echo-area motions, which are just the displacements observed during the preceding 1 hr. A test of the forecasting value of these data was made by applying them to the translation of echoes in the vicinity of St. Louis, Mo., for periods of 3, 6, and 9 hr. For each of these periods, over 800 pairs of translation and persistence forecasts calling for the occurrence or absence of echo area over St. Louis were made. All the available radar summary maps from August through December 1961 were used for the test.

The most important results pertain to 3-hr forecasts and are illustrated by Tables 4-II and 4-III. First, it is clear that the translation of echoes with their past movement produces forecasts that are markedly better than persistence. Excluding the forecasts and observations of an echo edge over St. Louis, 81.5% of translation forecasts calling for echo occurrence were correct, while only 72.1% of the persistence forecasts were correct. In other words, persistence forecasts of echo occurrence involved over 50% more errors than translation forecasts.* A similar relationship exists between forecasts of

*If there were no average difference between forecasts made by persistence and translation in the universal population of such forecasts, this result would be obtained by chance only 6.5% of the time.

TABLE 4-II

RESULTS OF ALL 3-hr TRANSLATION FORECASTS
OF ECHO AREA OVER ST. LOUIS

Forecast	Number of subsequently observed conditions		
	Yes	No	Edge
Yes (99 cases)	75	17	7
No (704 cases)	16	671	17
Edge (19 cases)	8	8	3

TABLE 4-III

RESULTS OF ALL 3-hr PERSISTENCE FORECASTS
OF ECHO AREA OVER ST. LOUIS

Forecast	Number of subsequently observed conditions		
	Yes	No	Edge
Yes (93 cases)	62	24	7
No (703 cases)	27	658	18
Edge (26 cases)	10	14	2

the absence of echo made by translation and persistence. Of the "no echo" persistence forecasts, 96.1% were correct; of the "no echo" translation forecasts, 97.7% were correct.*

Examining now the correctly forecast echo occurrences, we see that translation correctly forecasts 82.5% of echo occurrences, but persistence correctly forecasts only 69.5%.†

All the interesting results obtained are presented in graphical form in Figs. 4-1 through 4-6. These figures illustrate the results of the 6- and 9-hr forecasts as well as those tabulated and discussed above. Although the figures show that the accuracy of the forecasts drops considerably as the time period is extended to 6 and 9 hr, there is still reason for optimism concerning the value of radar as a forecast tool for these periods. Refined forecasting techniques and data-collection processes should produce improved forecasts. The discussion above and examination of the figures lead to the following general conclusions.

(1) Forecasts of echo area locations based on observed past motions (translation) are more accurate than forecasts of persistence

(2) Translation is the better forecasting method for the two seasons studied However, the autumn translation forecasts show a greater improvement over persistence than is the case in summer, and forecasting accuracies are generally higher in autumn than in summer.

(3) Accuracy of forecasts for all time periods, up to and including 9 hr, is improved by application of translation However, forecasting accuracy decreases markedly with time.

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*This difference is significant at the 4.5% level

†This difference is significant at the 2% level

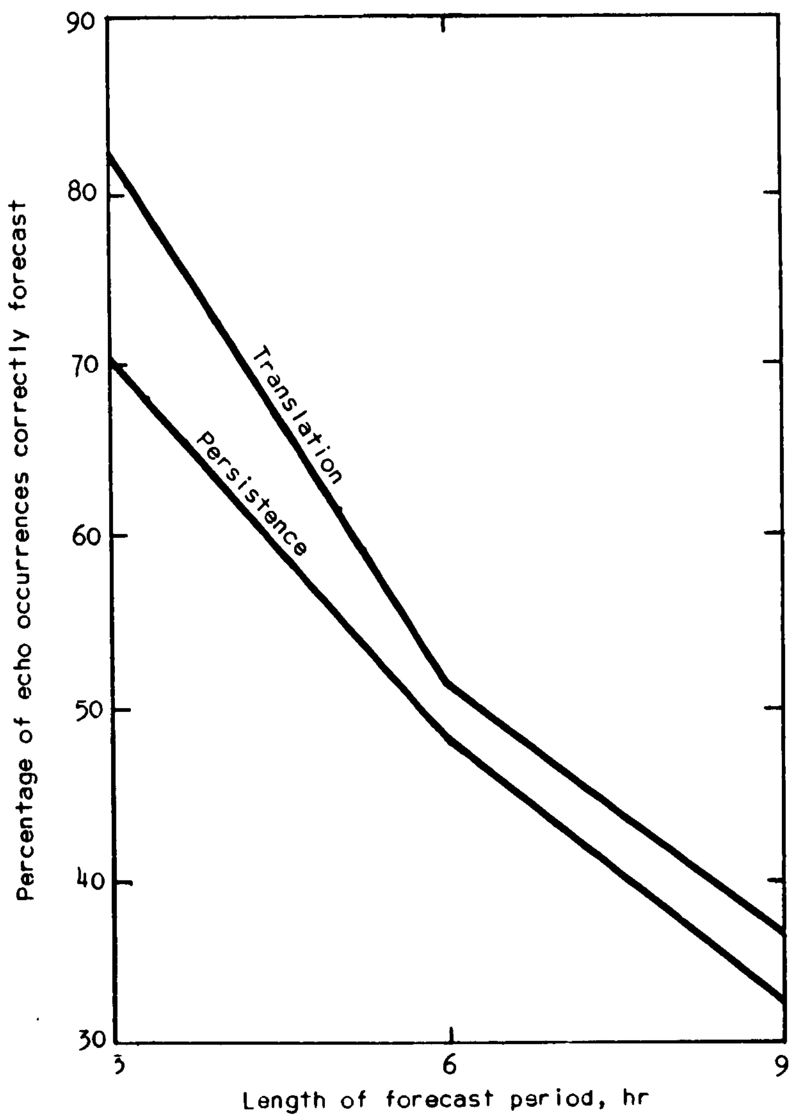

Fig. 4-1. Percentage of echo occurrences correctly forecast at St. Louis as a function of length of forecast period.

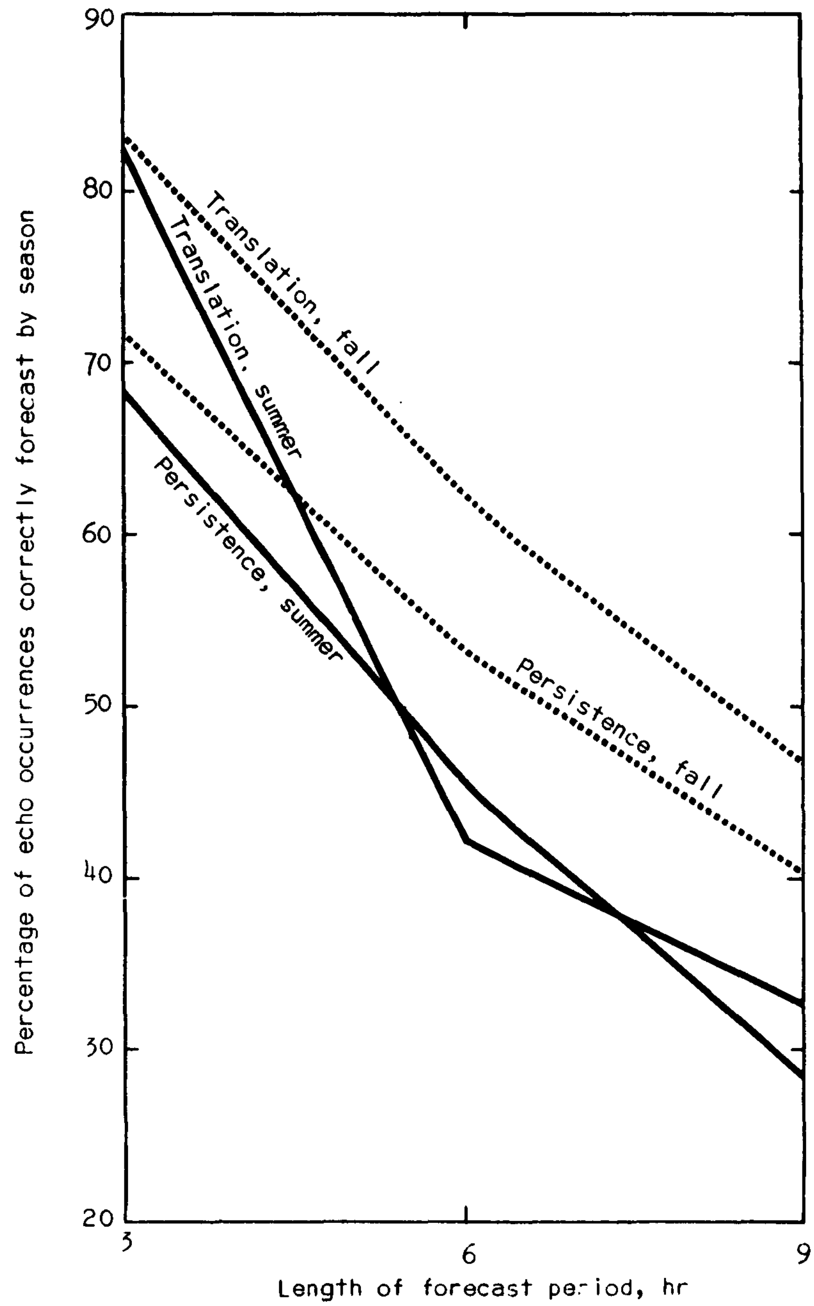

Fig. 4-2. Breakdown by season of results given in Fig. 4-1.

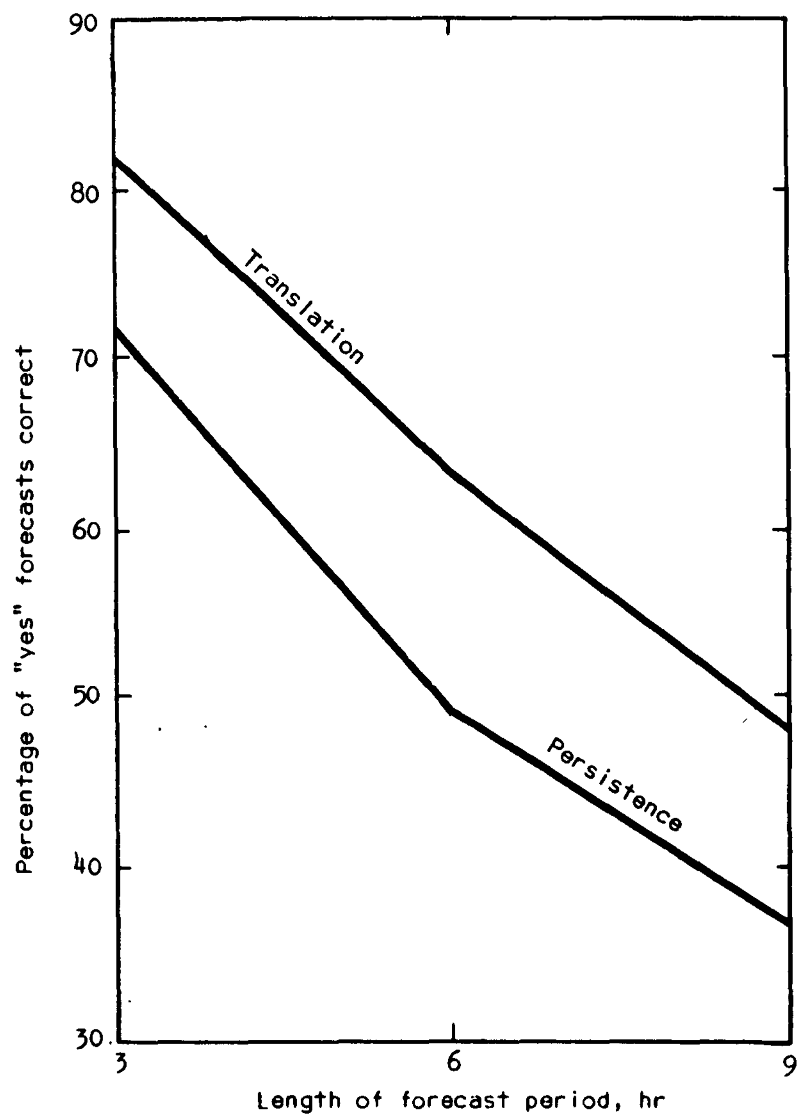

Fig. 4-3. **Percentage of "yes" forecasts correct as a function of length of forecast period.**

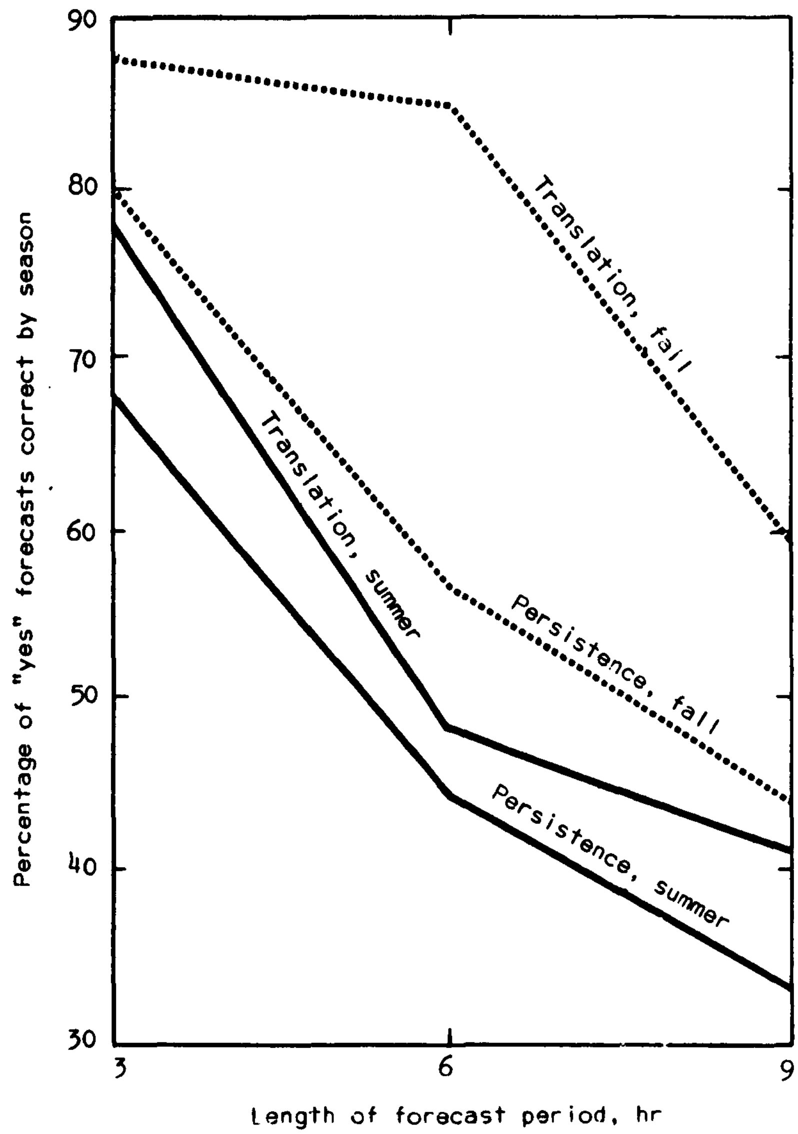

Fig. 4-4. Breakdown by season of results given in Fig. 4-3.

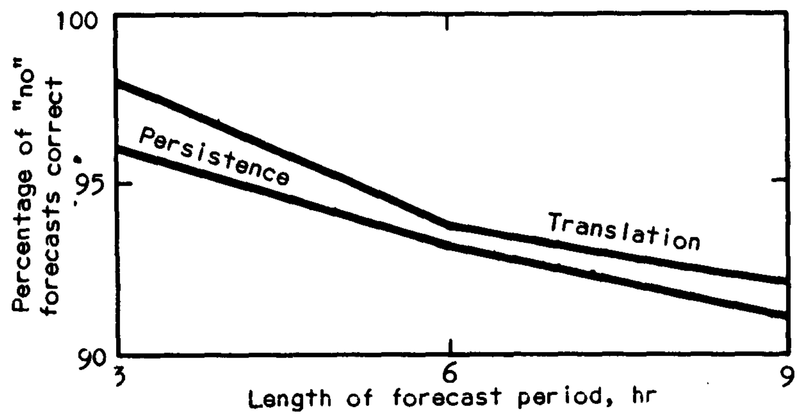

Fig. 4-5. Percentage of "no" forecasts correct as a function of length of forecast period.

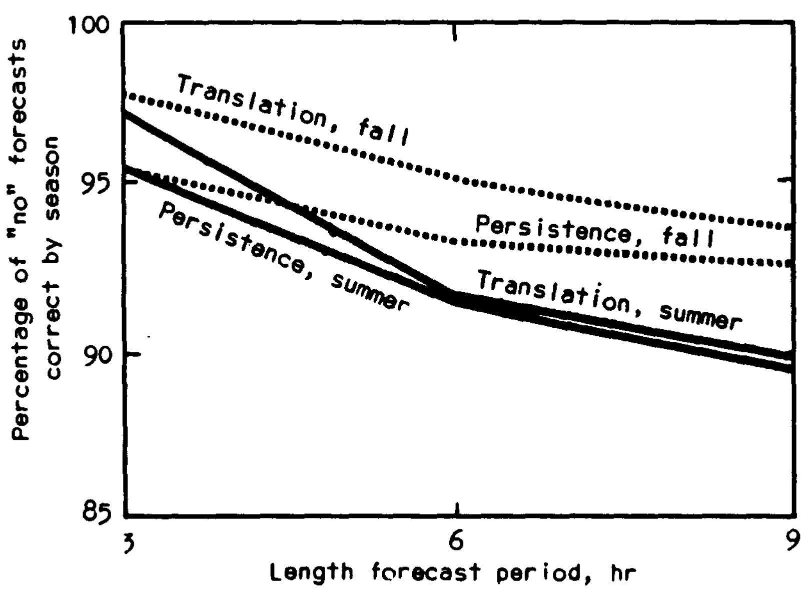

Fig. 4-6. Breakdown by season of results given in Fig. 4-5.

4.3 Predictability of Area Intensities

Neither the form of the hourly airways surface reports nor that of contemporary radar summary maps is well suited to the study of the relationships between echo intensity and precipitation rate. However, recent studies[8, 9, 10] have shown that measurements of precipitation rate and echo intensity are closely related and that intensity measurements could be a valuable aid in operational hydrology and severe-storm diagnosis. Therefore, we have studied the predictability of intensity through use of extrapolation of previous intensity changes.

The map transmitted each 3 hr from Kansas City frequently bears notations concerning the observed change of echo intensity during the preceding 1 hr. These notations have been used with the echo intensities reported on the maps 3 hr later to determine if the intensity-change notations have value for 3-hr predictions.

One hundred reports of 1-hr intensity increase, 100 reports of intensity decrease, and 100 reports of no change during 1 hr were used in conjunction with the associated later maps to prepare Table 4-IV. This table shows that, regardless of the intensity change in the past hour, it is most probable that the intensity will not change in the next 3 hr. Only about 30% of the intensity changes are predicted correctly, and it is apparent that on the basis of the reported intensities and intensity changes alone, the forecaster must always call for "no change."

The table also indicates, however, that the average change of intensity during the subsequent 3 hr tends to be in the direction of that reported during the previous hour. The χ^2 test shows that this indication is significant at the 1% level; it is what would be expected if there were important periods of at least about 8 hr in the intensity variations.* Since climatology and synoptic meteorology also give evidence that long-period intensity variations exist, it seems important to continue this study, using carefully measured radar signal intensities

*See Appendix A.

TABLE 4-IV

RELATIONSHIP OF REPORTED ECHO-INTENSITY CHANGE DURING PAST HOUR TO OBSERVED ECHO-INTENSITY CHANGE OVER SUBSEQUENT 3 hr

Past hour's intensity tendency	Intensity change 3 hr later		
	Increase	No change	Decrease
Increase (100 cases)	30	52	18
No change (100 cases)	12	68	20
Decrease (100 cases)	19	47	34

at 1-hr intervals when such data become available.

4.4 Probability Forecasting for Enroute and Terminal Conditions

Reed[9] has given a detailed plan for the combination of radar and routine data in objective analyses. The general nature of the data given on the radar summary maps is not well suited to point precipitation forecasts because echo locations are not given on a point basis. However, by multiplying the fractional coverage implied by the coverage symbol by the probability that a given forecast of area location is correct, an estimate of the probability that echo occurs over any particular point is obtained. And the probability that a given precipitation type, such as a thunderstorm, exists at a point could be obtained by consulting Fig. 3-2 and extrapolating the previously reported echo intensity and height.

Once the probability of the local occurrence of a given precipitation type is obtained, it can be related to the probability of occurrence along a flight path if it is assumed that the local probabilities refer to an "area of influence." In thunderstorms, this area might be that within which thunder can be heard at a surface station.

It might be assumed that the area of influence can be represented by a square whose side is of length s. The number of squares along a route of length r is then r/s. If we denote the probability of a thunderstorm in any one square by p, the probability of a thunderstorm-free flight is then $(1 - p)^{r/s}$, and the probability of encountering at least one thunderstorm square along the route is $1 - (1 - p)^{r/s}$. The probability of thunderstorms in all squares is $p^{r/s}$.

Even this simple analysis depends on the additional assumption that the probability of thunderstorm in the several squares is independent. This cannot be determined from present-day radar summaries, and it is evident that a proper study depends on standardized data, as Reed[9] has already indicated.

5.0 SUMMARY OF FORECASTING AND INTERPRETATION STUDIES

The studies discussed above show that the echo areas on the radar summary maps generally locate the areas of precipitation and that the intensity and echo tops in an area are valuable for estimating the weather type. The echo-area movement arrows on the charts, based on the observed movement during the preceding hour, are valuable for predicting the location of the areas 3, 6, and 9 hr later. The coverage indicators given on the summer maps correspond nearly as expected to the frequency of surface-precipitation reports within echo areas. During the cold season, the "scattered" and "broken" symbols are associated with more frequent surface precipitation, probably because much of the widespread precipitation characteristic of that time is not detected by the radars.

Neither the radar data nor the surface reports of precipitation are in a form suitable for defining a useful correlation between precipitation rate and echo intensity. The reported 1-hr intensity changes do show a significant positive correlation with the intensity change over the next 3 hr, although the best intensity fore cast one can make with present data is "no change." However, the existence of the correlation indicates both a measure of skill in radar-intensity observations and an apparent periodic component of the intensity, having a period of at least 8 hr.

Weaknesses of the present system can be associated with several aspects of the present radar observing and reporting procedures.* First is the very general terminology of the echo reports: locations and intensities of particular echoes are rarely given except for the occasional cases of especially intense cells. It is usually impossible to tell from the maps when echo exists over a particular place, and only the probability that an echo exists at a particular place can be specified.

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*It is evident that the lack of radar data over mountainous areas of the U. S. is also an important weakness of the present system. Note Fig. 2-1.

Second, the present system of encoding and reporting does not lend itself to modern computer techniques of data processing. In particular, the RAWARC code must be manually processed, and the maps must be visually interpreted.

Third, the subjective treatment of the data at practically every stage of collection and processing is associated with a multitude of effects that are practically impossible to evaluate and that introduce erratic elements into the time series of observations

That positive results have been obtained in this study despite the deficiencies in the data discussed above argues for a vigorous attempt to improve the present observing and reporting system. In view of the results, we have little doubt that weather analyses and forecasts of increased precision will be possible as the initial specification of echo locations and intensities improves The application of revised encoding and reporting techniques to improve the usefulness of the radar data is discussed in Section 6. 0.

6.0 RECOMMENDATIONS

There is little question that the radar summary maps can contribute substantially to the accuracy of in-flight and terminal weather analysis and prediction. However, the present format does not lend itself to analyses and forecasts of highest precision, nor does it provide the data needed for evaluation of the accuracy of precise forecasts. The increasing speed and density of air traffic require that weather conditions be defined in areas much smaller than the 10,000-mi^2 or larger regions most often depicted on present charts. This section and Appendix B outline a currently practicable system of observing and processing radar data. The system can produce much more radar-echo information than the present system, with no increase in manpower. Furthermore, the system lends itself to the mixing of manual and computer processing techniques essential at the current state of meteorological development, and it can be gradually modified to incorporate a greater proportion of computer processing as that becomes possible and desirable.

In essence, it is proposed that the radar operators at each station prepare a standard-format digitized code indicating the distribution of the important echo characteristics in squares about 25 mi on a side. There are about 5000 such squares within the United States.* Since there are about 120 such squares within 150 mi of a radar, the length of a message containing one character for each square with echo and some additional identifying characters

*A suitable national grid for radar data is formed by a cartesian-coordinate system laid over a Lambert conformal projection with standard latitudes within the United States. The angle formed between a parallel to the cartesian ordinate and a longitudinal meridian is $\theta = \sin \phi_0(\lambda_c - \lambda)$, where λ_c is the reference longitude and ϕ_0 is the standard latitude or the mean of two standard latitudes if there are two. With the reference longitude in the central U. S., the maximum angle (on the coasts) between the northward-tending lines of the cartesian grid and the local meridian would be about 15^o.

would be about the same as that of a typical hourly report of an airways station (see Section B.3).

Our tests have shown that a representative code embodying information in 50 squares can be prepared by the radar operator in about 10 min, which is comparable to the time presently required. Upon receipt, the coded message can be entered on a base map imprinted with the grids appropriate to each radar station in less than 2 min. Alternatively, the teletype data can be collated by a computer and a map of the whole country can be prepared automatically within a few minutes of receipt. In fact, it is reasonable to suppose that a computer could process the incoming data to separate the information of interest to particular users, prepare teletype tapes for RAWARC or facsimile transmission, and prepare current weather analyses and extrapolative forecast charts clearly illustrating the conditions of special interest to each class of user. For example, Fig. 6-1 is a simplified map (based on Fig. B-1) illustrating for aviation the locations of moderate or strong echoes above 25,000 ft and all other areas where echoes of any height and intensity (usually lower and weaker) are reported. Similar maps could be produced regularly, either manually or by computer, from a digital code of comprehensive content such as that suggested in Appendix B.

Since selection of a code is related to many special problems of each operating agency, and requires consultation among the agencies, the code and procedures in the appendix are intended to be suggestive only. Variations should be considered by the operating agencies from the viewpoint of their compatibility with various operating conditions and other features of the current system.

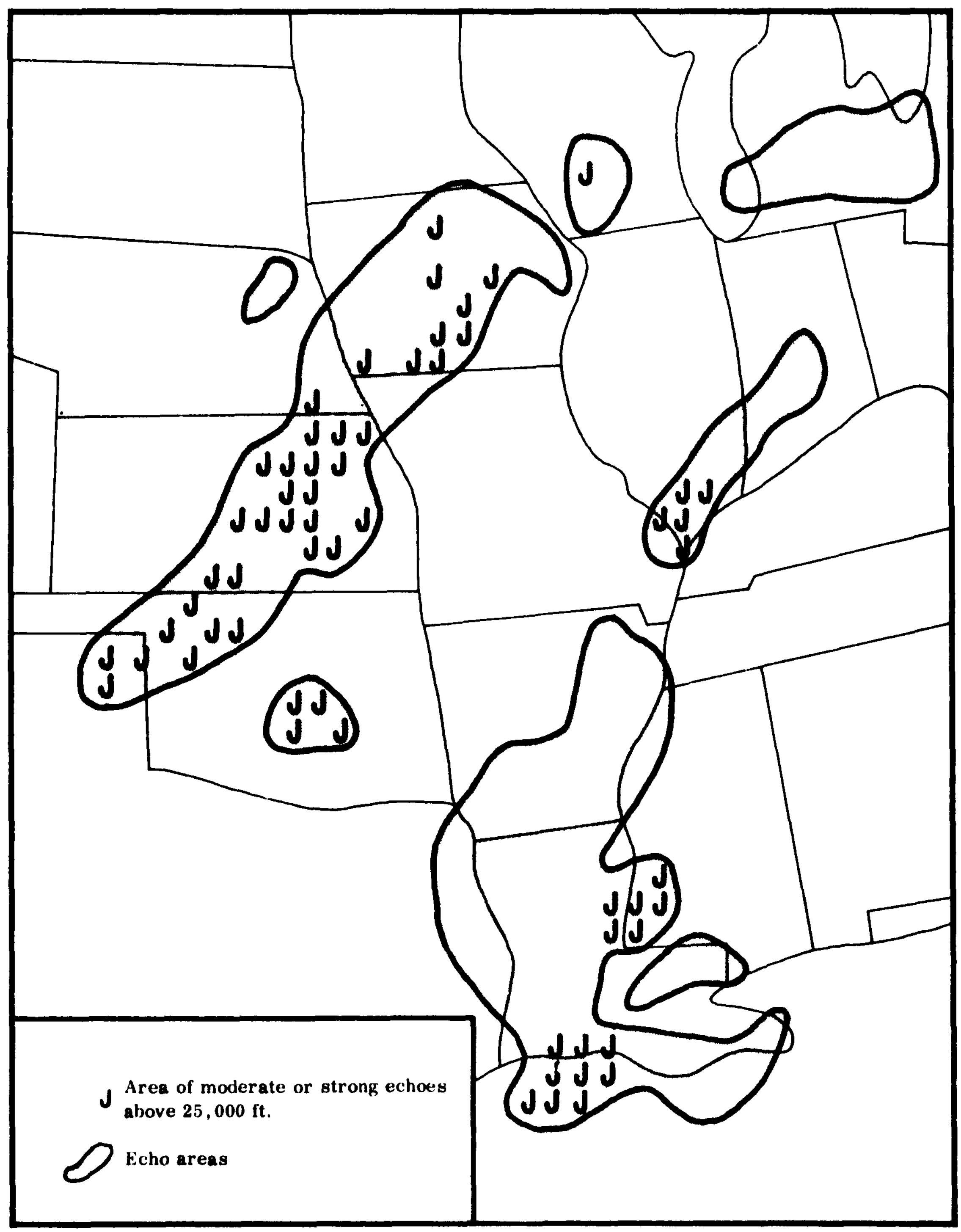

Fig. 6-1. Example of radar summary map for aviation.

APPENDIX A. RELATIONSHIP OF PERIODIC COMPONENTS OF RADAR ECHO INTENSITY TO PERSISTENCE OF ECHO-INTENSITY CHANGES

The tendency of intensity changes of like sign to associate is shown by the relatively large numbers in the central diagonal descending from left to right in Table 4-IV. In view of the significance indicated by the χ^2 test, this tendency is also attributed to the whole population. We inquire if any generalization can be made from this to the periods present in the data sampled. In attempting an answer, we examined values a, b, and c (Fig. A-1) of cosine functions of various periods, where the values are separated by 1- and 3-hr intervals. The parts of the periods wherein b - a and c - b have the same sign contribute to the result shown by Table 4-IV; the parts wherein b - a and c - b have unlike signs contribute to the opposite result. Since observations are equally likely to be made in any phase, the periods predominating in the real data should be among those which show like signs for the greater proportion of their span. A sample calculation is shown in Fig. A-1, and the results of our analysis of various periods are illustrated in Fig. A-2.

Figure A-1 illustrates a possible 12-hr period of echo intensity. Observations of intensity are made with equal frequency at all phases. The observations occur in sets of three, the second following the first by 1 hr and the third following the second by 3 hr. The two differences associated with the first observation set illustrated (b - a and c - b) have the same sign (both positive); the differences associated with the second set of observations have opposite signs. The phase intervals in which the initial observation is associated with like and unlike paired signs are also indicated on the diagram.

In this case, two-thirds of each 12-hr period is associated with like signs; such a 12-hr period, if present in the real series of intensity variations, would contribute to the tendency for grouping of like signs shown by Table 4-IV.*

*This result is actually independent of the time of the middle observation, b.

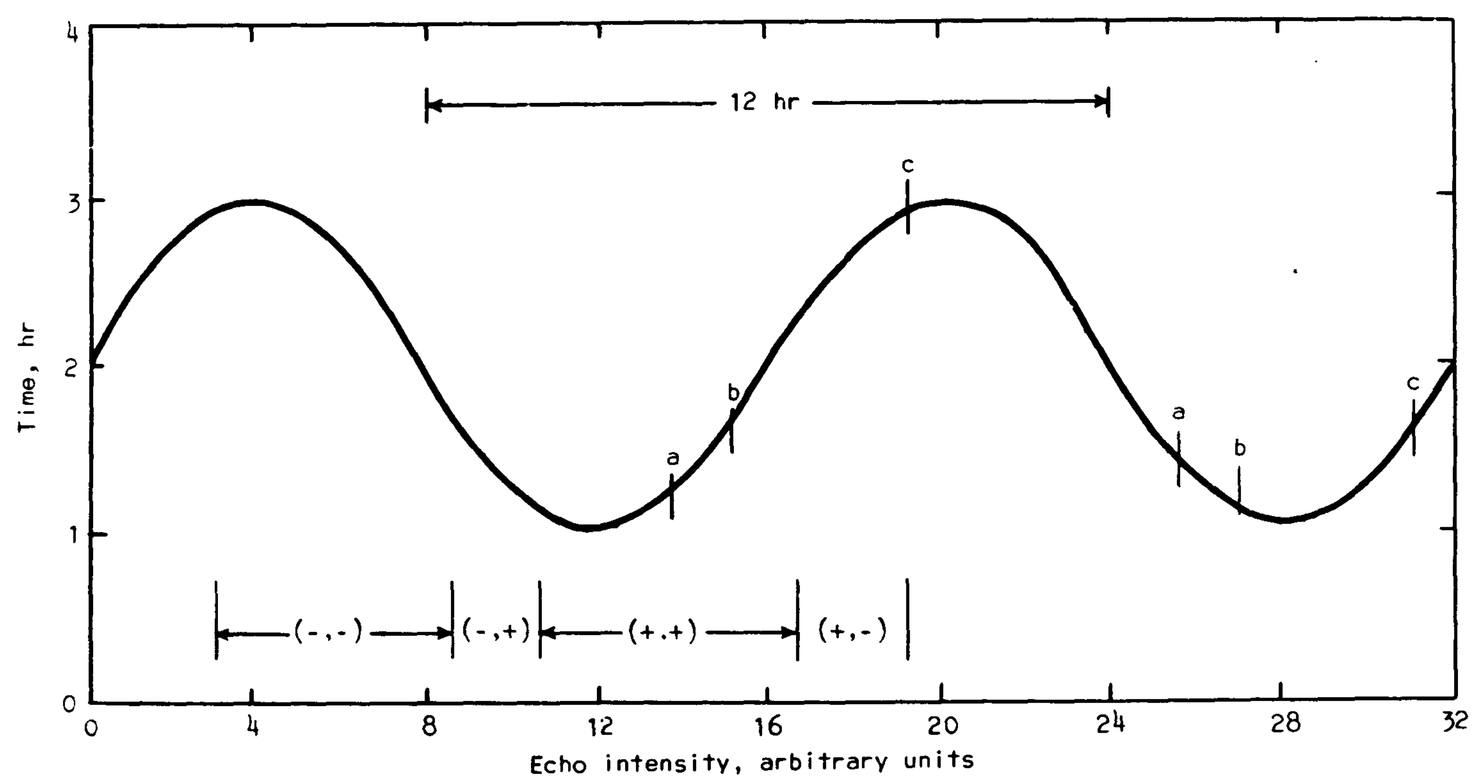

Fig. A-1. Illustrative calculation.

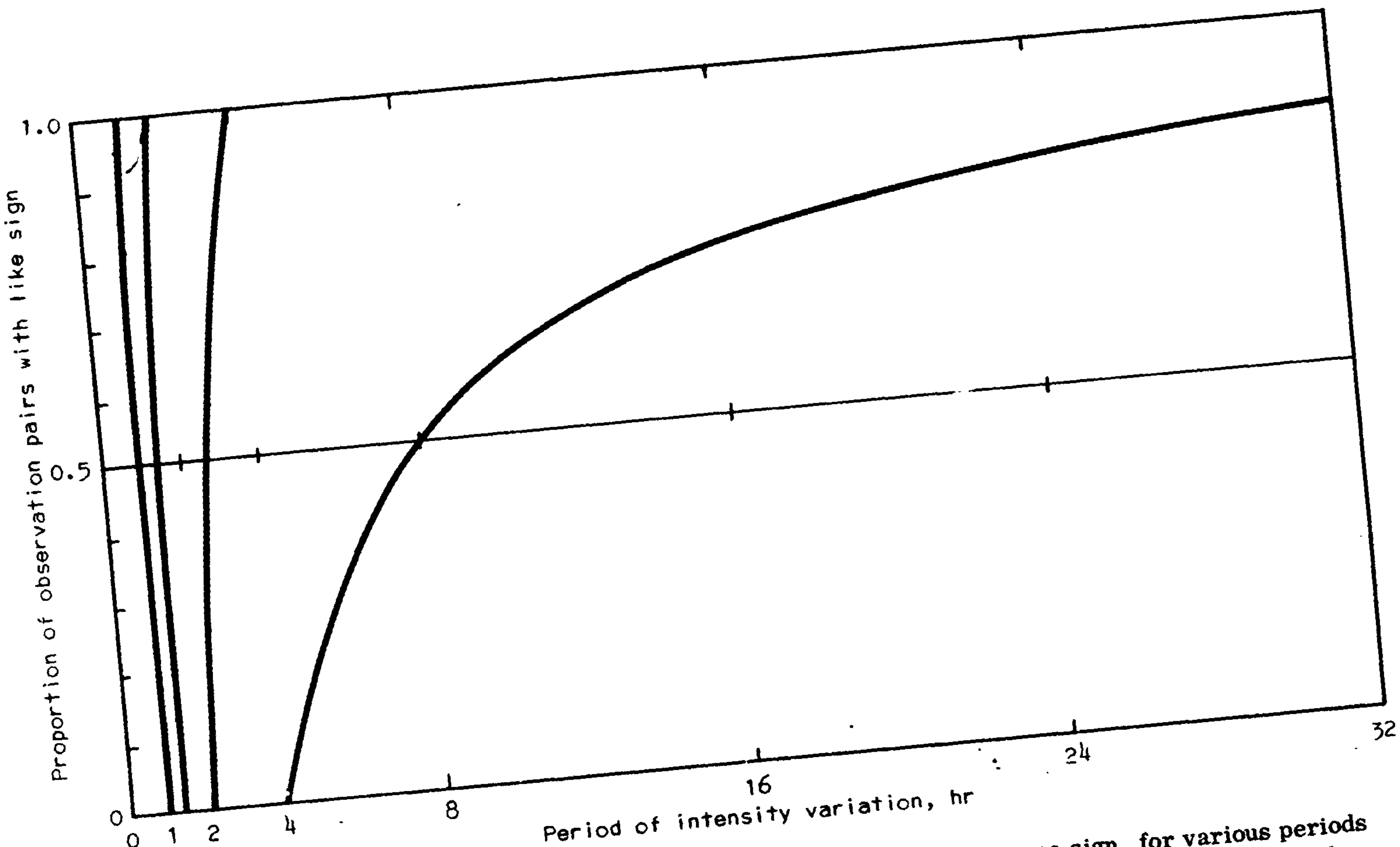

Fig. A-2. Proportion of observation pairs showing intensity changes of the same sign, for various periods of intensity variation. The ordinate shows the proportion of intensity observations a, b, and c during periods indicated by the abscissa in which the sign of b - a is the same as the sign of c - b, and where observations a and c are separated by 4 hr with the initial observation, a, evenly distributed with phase.

Although few absolute conclusions can be drawn from Fig. A-2 concerning the periods present in the data, it is evident that the presence of those longer than 8 hr would contribute to the results obtained, but the effect of periods shorter than 8 hr varies with the period. Although the predominance of selected periods shorter than 4 hr cannot be eliminated as a possibility, it seems more likely that the tendency indicated by Table 4-IV is due to periods longer than 8 hr; these could be the diurnal period or others corresponding to the growth and decay of large-scale meteorological systems. There is abundant reason to continue this study with improved data and to develop forecasting procedures based on the synthesis of the radar data with that of climatology and synoptic meteorology.

APPENDIX B. DETAILS OF SUGGESTED COLLECTING, ENCODING, AND REPORTING TECHNIQUES

B.1 General Procedure

The proposed method for digitizing radar data for national use embodies collection of data with the antenna at 0° elevation except in ground-return areas, where it is raised until the ground return is eliminated. Quantitative intensity information is obtained by using four different attenuator settings. The calibrated sensitivity time control (STC) switch is placed in the "on" position to help range-normalize the echo intensity.*

The intensity is given in the four categories now in use by the Weather Bureau: very weak, weak, moderate, and strong. The four intensity levels correspond to the theoretical precipitation rates shown in Table B-I.†

The fraction of each square covered by echoes of any intensity is given in two categories: less than 5/10 and from 5/10 to 10/10. A single digit specifying the coverage and intensity is placed in each echo-bearing square. Odd numbers are used for squares less than half covered, and even numbers are used for squares more than half covered. Also, the higher the number, the more intense the echo. (The code is presented in Table B-II.) When an echo believed to be dangerous is observed, the observer sends a 9 for the square and, at the end of the message, the top, intensity, and movement of the cell.

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*The STC should provide a 20-db reduction of system sensitivity at 10 mi with an increase to full sensitivity at 100 mi.[11, ¶ 2043.15] If the STC is not operative or not calibrated, the range can be normalized by applying particular sets of attenuation values at particular range intervals. If neither the attenuators nor the STC is working properly, the heights and coverages should be measured alone since such data will still be of great value and a marked improvement over the present system.

†Reference 11, Fig. 3-10, p. 3-42.

TABLE B-I*

THEORETICAL RAINFALL RATE AS A FUNCTION OF ECHO-INTENSITY CATEGORIES

Precipitation rate r, in./hr	Echo intensity
$1.00 \leq r < 5.60$	Strong
$0.20 \leq r < 1.00$	Moderate
$0.02 \leq r < 0.20$	Weak
$r < 0.02$	Very weak

*Reference 11, Fig. 3-10, p. 3-42.

TABLE B-II

DIGITAL CODE REPRESENTING ECHO COVERAGE AND INTENSITY

Coverage	Intensity			
	Strong	Moderate	Weak	Very weak
5/10 to 10/10	8	6	4	2
Less than 5/10	7	5	3	1

The height of the echo tops for a region are obtained in the same manner used in the present system. That is, the observer scans several echoes in the vertical to obtain an average echo top in an area. Letters are placed beside echo areas that correspond to the echo tops in that area. (The code is presented in Table B-III.)

Alternate. In the case of strong echoes, it may be desirable to know their tops. Instead of using the digits 7 and 8 for strong echoes, five letters could be used to indicate the echo top in five categories. (The code is presented in Table B-IV.) The code for strong echoes does not indicate coverage; however, it is believed that strong cells usually occur in conjunction with echoes that cover at least half a square and that, in any event, they should be given a wide berth by aircraft. Figure B-1 illustrates how Fig. 2-2 might have appeared had it been digitized according to this alternative method. The echo tops are represented by large letters in accordance with Table B-III.

The barbed arrows are the area-movement indicators for the echoes in the vicinity of the arrow and indicate the movement of the echo area in the past hour. The movement could be determined by personnel at the central receiving station (which might be Kansas City), or it could be determined by computer, using the linear lag correlation technique discussed by Hilst and Russo.[4] If a computer is used, it would be feasible to produce maps showing the conditions expected one, two, or more hours hence, and to omit the movement arrows.

B.2 Step-by-step Procedure of Collecting Digitized Data

(1) Place a transparent overlay ruled with a grid with squares 25 mi on a side over the PPI scope.

(2) Adjust PPI scope to 150-mi range; turn STC on.

(3) Set elevation at 0^{o} and attenuation at 45 db, and scan for echoes outside the ground-clutter region

(a) When an echo is detected place an S in the box.

TABLE B-III

CODE FOR ECHO TOPS

Echo height h, ft	Code
$45,000 < h$	VH
$35,000 < h \leq 45,000$	H
$25,000 < h \leq 35,000$	M
$15,000 < h \leq 25,000$	L
$0 < h \leq 15,000$	VL

TABLE B-IV

ALTERNATIVE CODE FOR STRONG ECHOES

Echo height h, ft	Code
$55,000 < h$	Y
$45,000 < h \leq 55,000$	X
$35,000 < h \leq 45,000$	W
$25,000 < h \leq 35,000$	T
$0 < h \leq 25,000$	R

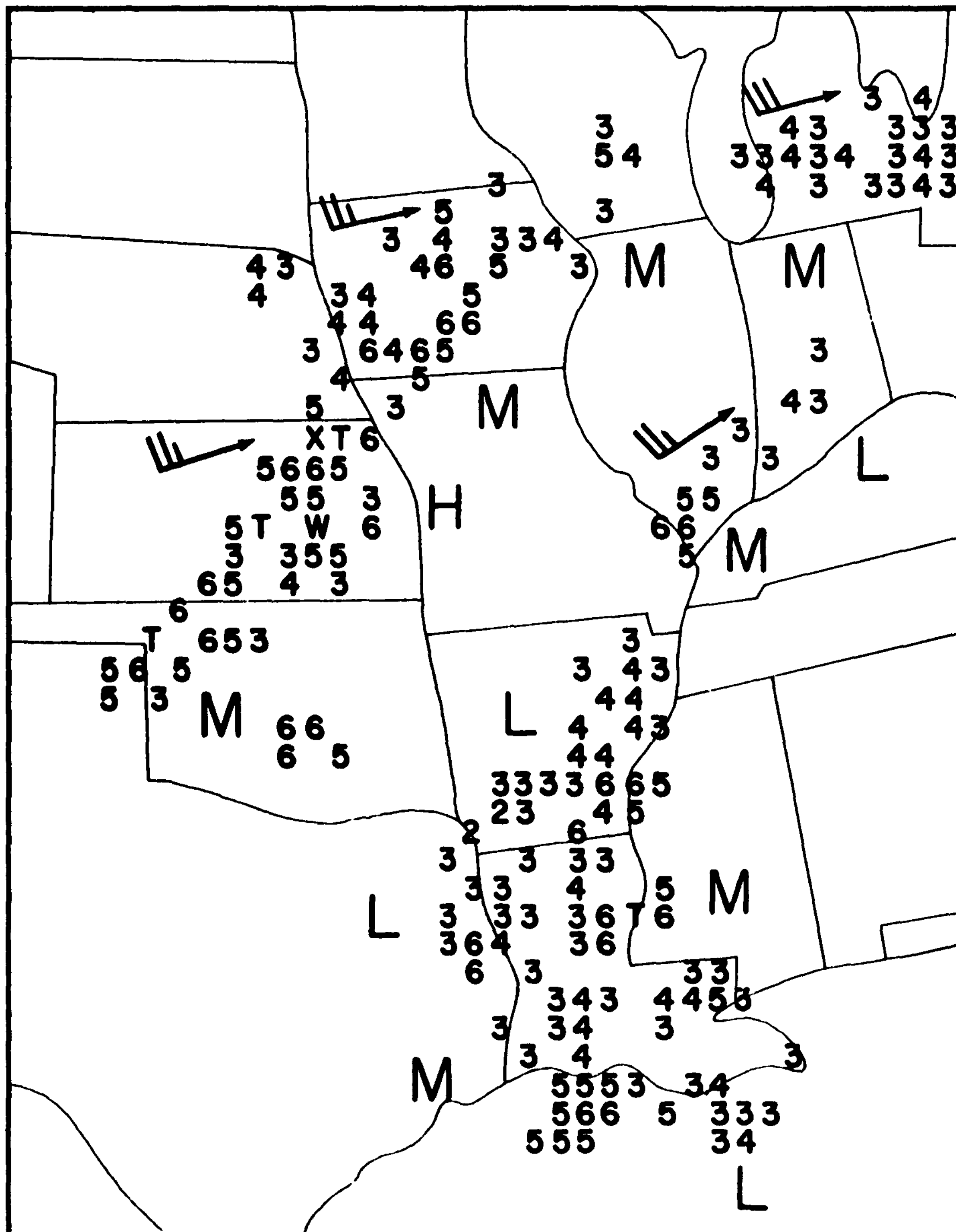

Fig. B-1. Example of a digitized radar summary. For explanation of symbols, see Fig. 2-2 and Tables B-II, B-III, and B-IV.

(b) Adjust attenuation to 33 db and place M's in any additional squares containing echoes.

(c) Adjust attenuation to 15 db and place W's in any additional squares containing echoes.

(d) Set attenuation at 0 db. For each square containing echoes, determine the coverage. Enter a digit in every box containing echoes, using Table B-II.

(4) In the ground-clutter region, raise the antenna to clear the ground clutter and run through all the steps under (3) for the squares in the ground-clutter region.

(5) Scan several echoes in the vertical to obtain an average height of the various echo areas. Enter the proper letter that corresponds to the average echo height (see Table B-III) in an empty box close to the echo area.

(6) If an echo that is considered dangerous appears, enter the digit 9 in the square in which it is located. Measure the intensity, height, and movement of the cell, and add this information at the end of the teletype message.

Alternative. Same as steps (1) through (6) except for step (3a).

(3a) When an echo is detected at 45 db, scan the echo vertically at 0 db, and determine the height. Place the appropriate letter as given by Table B-IV in the square.

B.3 Procedure for Encoding and Transmitting

The grid overlay for the PPI scope has the address of each square centered in its proper place. Each square has an address, corresponding to its row and column number. Many coding procedures are possible. One simple procedure is based on the following rules.

(1) Only squares containing echoes are coded.

(2) The most northern row is coded first, beginning with the most western echo in the row.

(3) The address of the most northwestern square with echo is given, followed by the digit assigned to that square. Without skipping a space or readdressing, enter the remaining digits or letters for the row.

(4) After a row is coded, go to the next most northern row and address the most western echo, and continue as in step (3).

(5) If no echo appears at a square, enter a dash (-). If four or more dashes occur simultaneously, don't enter dashes, but readdress the next echo-containing square.

(6) Any additional information, such as the cell movement of a very severe storm, will be entered at the end of the message in plain language.

<u>Example.</u>

	A	B	C	D	E	F	G	H	I	J	K	L
A				-	-	-	1	5	-			
B			-	-	-	5	5	3	L	-		
C		-	1	5	-	-	3	5	1	-	-	
D	-	-	2	8	7	-	-	1	-	-	-	-
E	-	M	1	7	5	-	-	-	1	-	-	-
F	-	-	-	1	-	-	-	-	-	1	-	-
G	-	-	-	-	-	-	1	-	-	-	-	-
H	-	-	-	-	-	-	-	-	-	-	-	-
I	-	-	-	-	-	-	-	-	-	-	-	-
J		-	-	-	-	-	-	-	-	-	-	
K			-	1	5	-	L	-	-	-		
L				-	6	1	-	-	-			

<u>Example encoded.</u> AG15 BF553L CC15--351 DC287--1 EBM175---1 FD1 FJ1 GG1 KD15-L.

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